Electromagnetic Interference from LED Lamps

Fourteen examples compared

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For more than a hundred years 'artificial light' has almost exclusively meant incandescent lamps. However, the relatively low output of incandescent lamps has been criticized and has ultimately led to their being banned in the EU. Low-energy fluorescent lamps are certainly more efficient, but they do not work well when turned on and off frequently, and they contain not exactly ecologically-friendly quantities of mercury. As LED lamps become cheaper to buy it seems that semiconductor-based lighting is the ideal replacement. So that's all good then. Or is it?

Well, it depends: there have been reports of LED lamps causing electromagnetic interference. Reason enough for Elektor to try to get to the bottom of things.

As suggested above, low-energy fluorescent lamps enjoyed only a few brief moments of popularity. Their toxic chemical content is indeed a problem; but so is the quality of the light produced, and more particularly their behaviour when turned on: it takes some time after power is applied before the bulb reaches full brightness. It is also far from ideal that the service life of the bulbs is considerably reduced if they are turned on and off frequently. Low-energy fluorescents have almost disappeared from the market now, as LED lamps have increased in efficiency and light output and fallen significantly in price. LED lamps are also available in a very wide range of shapes, socket configurations and colour temperatures. They usually reach full brightness immediately they are switched on, they are hardly, if at all, affected by being turned on and off frequently, and (apart from a few dodgy ultra-low-cost examples) their service life is pleasingly long. LED lamps are thus both ecologically and economically sound. So it would seem on the face of it that all our problems are solved and we can turn our attention to other matters.

Table 1. List of lamps tested.

#	Manufacturer	Type	Power	Output (lm)	Efficiency (lm/W)	Weight	Flicker	f1	VHF	SW
0	Osram	Incandescent bulb	60.0 W	710	11.8	23 g	yes			
1	Osram	AB48940	9.5 W	806	84.8	43 g	—			
2	Blaupunkt	ILUA70-16WB B P	16.0 W	1521	95.1	72 g	—			
3	Philips	A60 7W12430	7.0 W	806	115.1	41 g	slight			
4	Müller Licht	400006	5.5 W	470	85.5	34 g	yes			
5	Müller Licht	Retro LED 400223	4.0 W	470	117.5	17 g	—			
6	Osram	LED Star Classic A60	7.0 W	806	115.1	29 g	—			
7	Toom	G60	10.0 W	806	80.6	63 g	—			
8	Opple	LED-EG50-E27	6.5 W	470	72.3	82 g	—			
9	Sygonix	TLK-A60-806PM	9.5 W	806	84.8	94 g	—			
10	IKEA	Ryet 1000	11.5 W	1000	87.0	72 g	—			
11	IKEA	LEDARE 600	8.6 W	600	69.8	78 g	yes			
12	IKEA	Ryet 400	5.0 W	400	80.0	40 g	—			
13	IKEA	LEDARE 1000	13.0 W	1000	76.9	122 g	yes			
14	B1	LED lamp	8.8 W	806	91.6	52 g	—			

Signs of trouble?

At the beginning of September 2017 Elektor received a report from a member of the German amateur radio club DARC that suggested that significantly increased levels of electromagnetic interference affecting broadcast radio, amateur radio and WLAN signals could be traced to LED lamps. We took up the issue in an article online [1]. The German-language version of this article alone attracted over 100 000 clicks.

At the end of 2016 the club published on its website a list of various manufacturers' LED lamps along with spectral plots [2], and the October 2017 issue of the club magazine 'CQ DL' included an article describing the measurements. The German 'Stiftung Warentest' consumer product testing organization also looked at LED lamps, but not with regard to electromagnetic interference. And so it falls to Elektor to look at the question in more detail: in this article we will take a closer look at 14 LED lamps, and give a brief guide to how you can find out for yourself to what extent your own LED lamps are polluting the ether, without the use of large banks of test equipment.

Procedure

First we visited IKEA, our local DIY shed, and the Internet, purchasing a total of 13 different LED lamps with E27 fittings. To them we added a further lamp supplied by an interested colleague. These 14 lamps provide a sample of the market, and include products from well-known companies, 'no name' brands and the DIY shed's own-brand products. The sample is not fully representative but nevertheless provides a good cross-section of what it is possible to buy today. Table 1 gives a list of the lamps we examined, the main characteristics of each, and a qualitative indication of the results of our testing as a colour (green=good, yellow=OK, orange=fair, red=poor).

Of course there is still a lot more to be said. Because anyone interested in electronics will (rightly enough) be keen to know more about the whys and wherefores of our testing, the following pages give more background regarding the mea-

surement techniques we used, including some sample oscilloscope traces.

Interference

First we should look at how various kinds of interference can arise. The power networks in Europe supply approximately sinusoidal AC at a voltage of 230 Veff and a frequency of 50 Hz: in other words, we should expect a low-frequency signal without any significant harmonics to cause interference. In reality, however, there are dimmers, electric motors, switching power supplies in PCs and other devices to contend with, which, in conjunction with the resistive and inductive components of the household wiring, conspire to distort the pure sinewave to a greater or lesser extent. The result is a spectrum containing harmonics extending into the high-frequency RF bands. In turn this affects other devices that depend on interference-free radio signals to transmit and receive information. This includes broadcast radio receivers and amateur radio transceivers, to name just two categories.

In lower-tech days there were fewer sources of interference. The good old-fashioned incandescent bulb is basically just an ohmic piece of resistance wire, passing a sinusoidal current without distorting it. The humble incandescent bulb would also never be party to such dirty tricks as phase shifting or the like at any point in its brief existence.

However, the situation with LED lamps is completely different. It is well known that LEDs should be operated at a constant current because, like all semiconductor diodes, they exhibit a rather low differential resistance in the neighbourhood of the nominal forward operating current, and their forward voltage has a negative temperature coefficient. In the simplest designs both these effects can be smoothed out by the use of a series resistor in conjunction with a higher supply voltage than is strictly necessary. At its nominal operating current the forward voltage of a white high-power LED is around 3.3 V. For example, it is possible to use a series resistor to operate such an LED simply and safely from a 5-V voltage source. However, in this simple configuration around one third of the power consumed by the circuit is dissipated in the series resistor as heat, and so it is only suitable for driving smaller LEDs, for example those used as indicators. Beware, however, that the LED strips sold for DIY applications generally consist of groups of three LEDs plus one protection resistor in series, the groups being wired in parallel across the 12-V supply. These strips dissipate about 20 % of the power consumed as heat in the resistors.

On the other hand it should be said that the direct operation on LEDs at constant voltage in this way, although suboptimally efficient, has impeccable credentials from the viewpoint of electromagnetic interference. The arrangement causes no distortions to current waveforms and therefore generates no RF. However, LED lamp manufacturers are keen to make the most efficient devices possible, and to do this they have to eschew the simple series resistor in favor of switching power supply techniques. And that is where the problems start.

AC line operation

First we should mention an exception to the discussion below. In the article 'Let There Be LED' in the January & February 2016 issue of Elektor [3] Thomas Scherer looked at the LED shown in Figure 1, which was advertised as a 10-watt bulb. Had it not fallen to pieces inside its box during shipping, he would not have noticed what a strange product he had acquired: not only had the switching power supply been dispensed with and replaced with a series capacitor, but it also became apparent that the lamp was in fact only a 7 W model. The advantage of these economies was that the lamp produced hardly any electromagnetic interference. The same approach is used in modern imitation 'filament' lamps, which are in fact made from long rows of LEDs arranged to look like retro-style incandescent bulbs.

Some 90 % of all LED lamps, however, contain a full switching power supply that delivers at its output a constant current suitable for the series string of LEDs, typically either a small number of power LEDs or a large number of smaller LEDs. The circuit works as follows. As in any ordinary switching supply, the AC line input is first rectified and then smoothed using a high-voltage electrolytic capacitor. The resulting DC voltage is then electronically 'chopped up' and fed to a small transformer. The current flowing from the output of the transformer is measured and used as feedback to the electronics that controls the switching transistor. Typical switching frequencies are in the range from 30 kHz to 100 kHz: the fundamental and second harmonic thus have fairly low frequency in RF terms. The signal driving the transformer, however, is far from a sinewave: it is more like a squarewave with very fast edges. The fast switching edges mean that the RF spectrum includes many higher harmonics of the switching frequency at considerable power. Fast switching is good for the efficiency of the circuit, and a higher switching frequency is good for the mechanical design, as it allows a smaller transformer to be used. Unfortunately both these pressures act to increase the level of RF interference. Filtering to try to attenuate the interference adds to circuit complexity and hence cost, and negates the advantage of a physically smaller circuit design; for this reason, many designs only feature limited filtering.

Figure 1. Innards of a low-cost LED lamp: dropper capacitor, diode, filter capacitor and discharge resistor. The silk screen legend gives it away: 7 W, not the claimed 10 W!

Test and measurement

To make sure that we exercised the various lamps under identical conditions we set up a test environment. The first stage, as is apparent from Figure 2, is to isolate the set-up from the mains supply using a transformer: this helps protect both the test equipment and its operator. The four taps on the secondary side of the transformer, at 15 V intervals, let us test whether the lamp brightness varies significantly with changes in the supply voltage.

The ground of the circuit is connected to mains earth so that it can in turn be connected to the ground of an oscilloscope. The current through the LED lamp is mea-

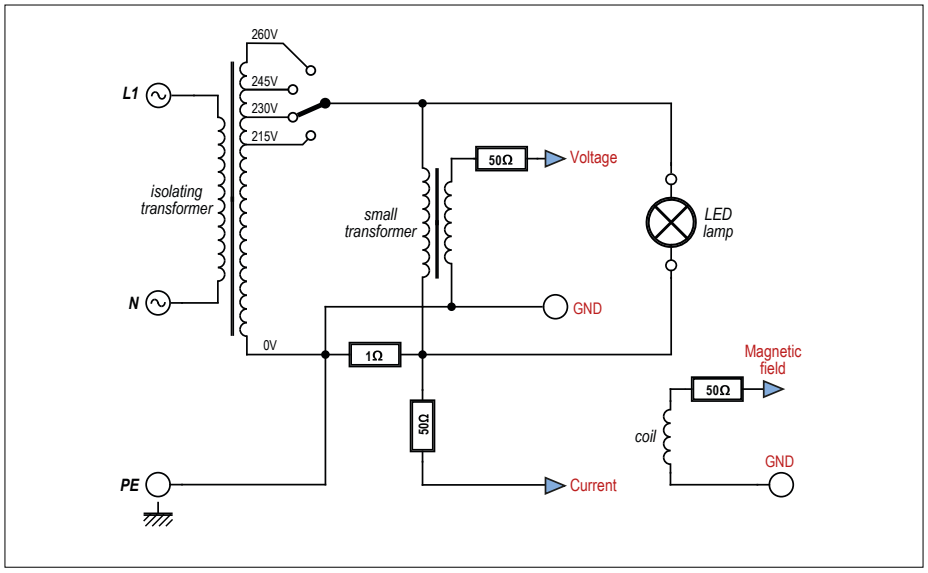

Figure 2. Test set-up for measuring LED lamps.

sured using a 1 Ω shunt resistor, with a further 50 Ω resistor providing impedance matching to the connected BNC cable. A small mains transformer in parallel with the LED lamp provides a stepped-down voltage on its secondary side proportional to the supply voltage. This allows us to measure interference on the voltage signal, and in particular provides a convenient way to trigger the oscilloscope.

Our arrangement allows us to measure current and voltage waveforms safely and accurately. But we want to go further than that: we add a suitable receiver coil to measure the stray magnetic field and an antenna for the electromagnetic field. We will look at these latter two measurements in more detail below.

We are not just interested in the time-domain behaviour of the current draw of the lamp: we also want to examine its spectrum.

In order to clearly identify our 14 LED lamps (plus the incandescent bulb we are using as a reference) we have numbered them as listed in Table 1 and these numbers are used to label our figures and screenshots. The photos in the page borders show the sample lamps we tested.

Current waveforms

As an experimental control we measured the waveform of the current drawn by a 60 W incandescent bulb. We do not have a photo of the lamp itself, but the plots show us what to expect from an interference-free lamp. Even when the mains voltage waveform is slightly distorted, we can see from the voltage (purple) and current (yellow) traces in Figure 3 that there is no interference. The trace colour scheme is the same in the plots for the LED lamps in Figure 4 to Figure 17.

The current waveforms immediately provide us with our first surprise. The first lamp we tested (see Figure 4) exhibits sharp current spikes in its current waveform near the extremes of the voltage waveform, rather than a smooth sinusoidal or trapezoidal shape. The needle-like spikes correspond to the points in time

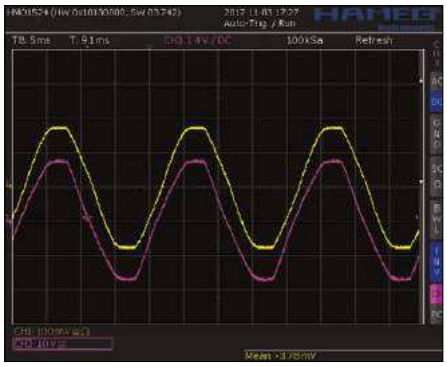

Figure 3. Current and voltage traces from the incandescent bulb.

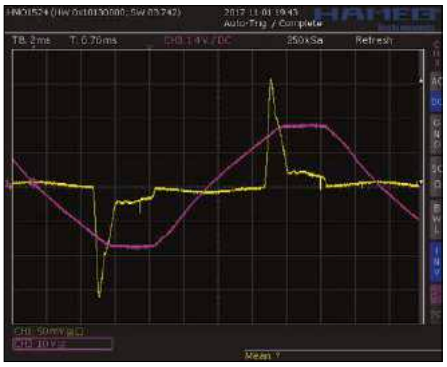

Figure 4. Current and voltage traces from lamp 1.

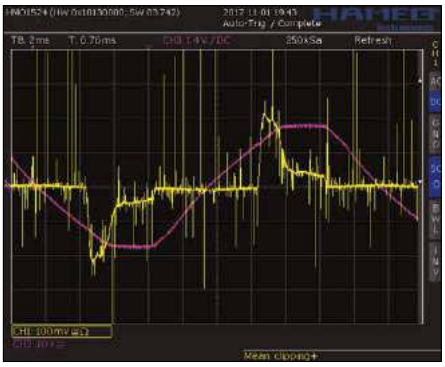

Figure 5. Current and voltage traces from lamp 2. Oh dear!

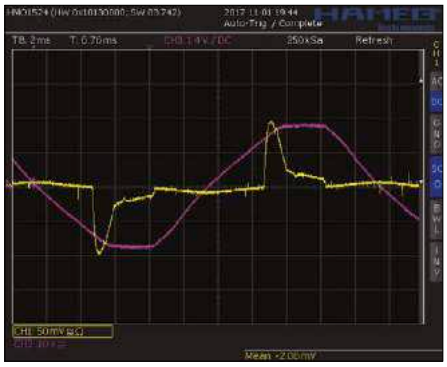

Figure 6. Current and voltage traces from lamp 3.

Figure 7. Current and voltage traces from lamp 4.

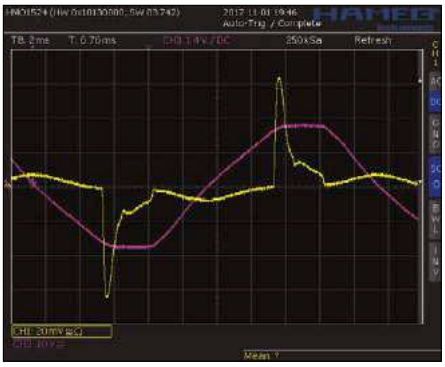

Figure 8. Current and voltage traces from lamp 5.

where the smoothing capacitor is charged back to its peak value. The following relatively flat region of current consumption, which looks like the seat of a chair, corresponds to the current drawn by the LEDs while the smoothed voltage is relatively constant. Once the supply voltage falls sufficiently the circuit is powered only from the smoothing capacitor, and no current flows from the mains until the mains voltage again exceeds the capacitor voltage, during the next half-cycle. A glance at Table 1 shows that this lamp does generate some interference in the VHF band, even though the current waveform looks relatively smooth.

However, if you think the current waveform for lamp 1 looks bad, you will find Figure 5 a sight for sore eyes. In addition to the charging curve that we saw for lamp 1, there is also a large number of very sharp spikes with an amplitude easily double that of the charging spikes. It doesn't look great. And indeed, as Table 1 reveals, this is among the worst of the lamps we tested.

The general shape of the current waveform for lamp 1 is also seen in the traces for lamps 3, 4, 5, 6, 8, 9, 10, 12 and 14. However, take a look at Figure 14 and Figure 16 (lamps 11 and 13 respectively). The current waveform has no charging peak: it is just a relatively smooth, roughly trapezoidal curve with a slight phase shift. The electronics in these devices must be charging the smoothing capacitor at a reasonably constant (and therefore low) current, beginning when the supply voltage reaches just a few tens of volts and lasting for a correspondingly long fraction of the half-cycle. The period where no current flows is very brief. In RF terms the performance of lamp 13 is excellent: practically no interference. Lamp 11 is nearly as good, and IKEA could claim two top spots if the nasty little spikes visible in Figure 14 were eliminated. It would seem that IKEA is purchases devices from more than one supplier.

Figure 10 paints a more ambiguous pic-

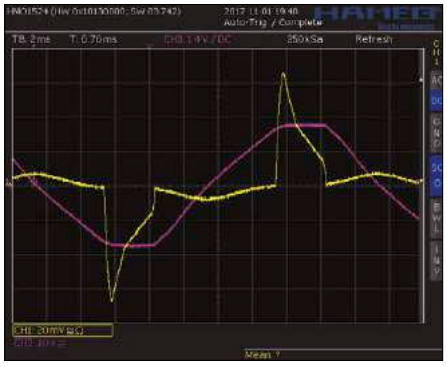

Figure 9. Current and voltage traces from lamp 6.

Figure 10. Current and voltage traces from lamp 7.

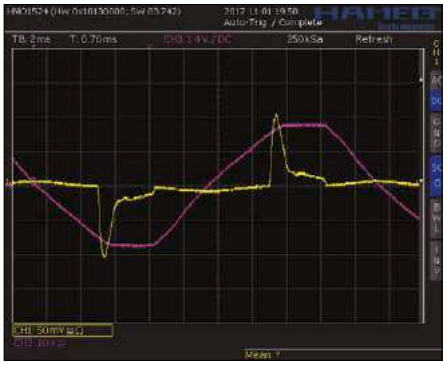

Figure 11. Current and voltage traces from lamp 8.

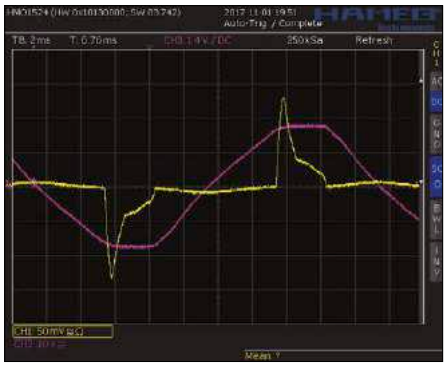

Figure 12. Current and voltage traces from lamp 9.

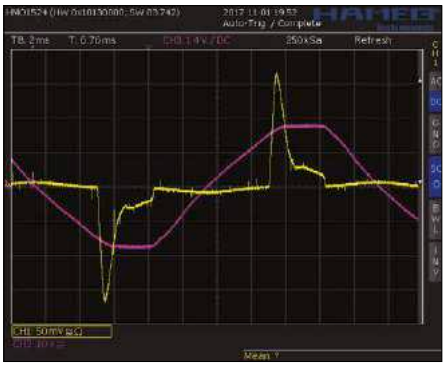

Figure 13. Current and voltage traces from lamp 10.

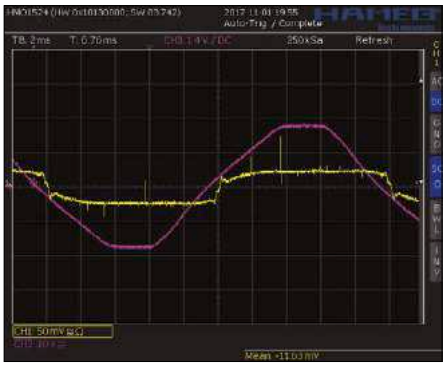

Figure 14. Current and voltage traces from lamp 11.

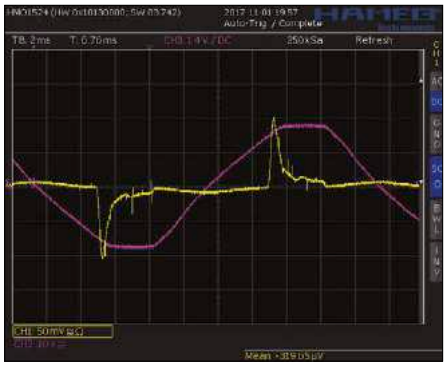

Figure 15. Current and voltage traces from lamp 12.

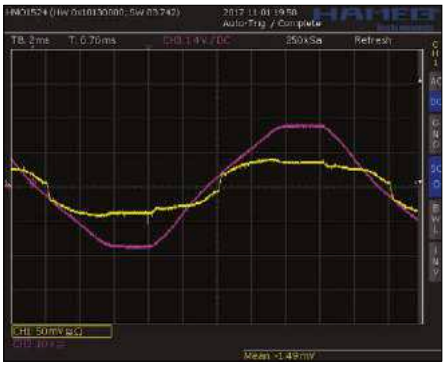

Figure 16. Current and voltage traces from lamp 13.

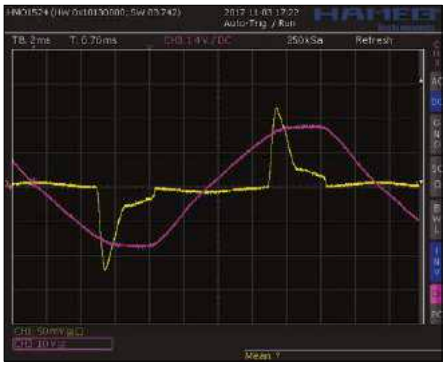

Figure 17. Current and voltage traces from lamp 14.

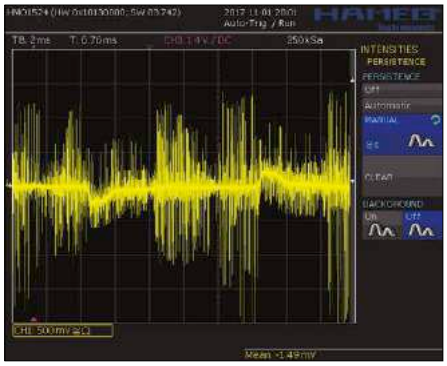

Figure 18. Current trace with persistence enabled: lamp 11.

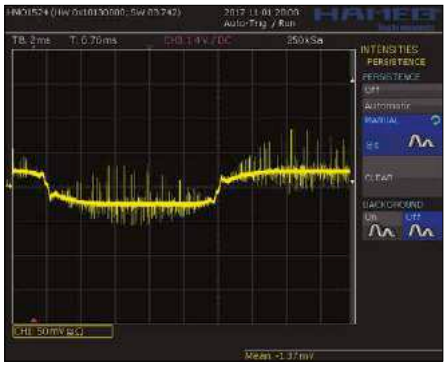

Figure 19. Current trace with persistence enabled: lamp 2.

ture. It appears that the lamp charges its smoothing capacitor when the voltage reaches about half its peak value, both starting and stopping suddenly; in between there is a further charging spike as we saw in many of the other lamps. Perhaps a good idea with a poor implementation? The sharp edges to the waveforms suggest that we should expect some RF interference, and indeed this lamp from IKEA receives an orange warning in Table 1, the second worst interferer in our tests.

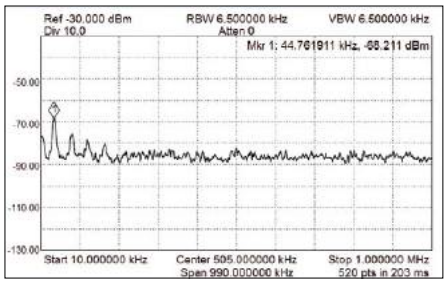

Figure 20. Current spectrum for lamp 1.

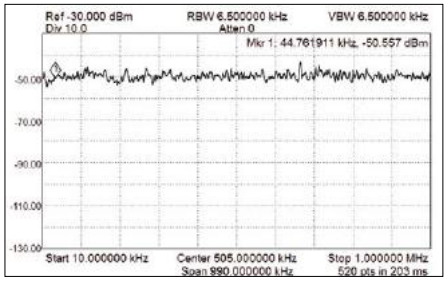

Figure 21. Current spectrum for lamp 2. No surprises there!

Current with 8-s persistence

Because the spikes are understandably responsible for the majority of the interference, it is helpful to look at the current waveform with persistence enabled on the oscilloscope. This makes the narrow spikes much bolder and so easier to see. The comparatively innocent-looking spikes in Figure 14 are thus transformed into the forest shown in Figure 18. It is now clearer why lamp 11 generates so much interference.

Just as dramatic an effect is seen with lamp 2. Figure 19 shows an impressively uniform series of spikes at all points along the current waveform.

Current spectrum

Our next step was to measure the spectrum of the current draw using a Signal Hound type USB-SA44B analyzer. A 220-nF capacitor was used to block the DC component of the signal, and in combination with the 50 Ω termination impedance forms a high-pass filter with a cutoff frequency of around 15 kHz. This is a convenient way to achieve considerable attenuation of the 50 Hz and 100 Hz components, as well as their first few harmonics. The addition of a Mini Circuits FTB-1-6 balun, with an operating frequency range of 10 kHz to 125 MHz, galvanically isolates the instrument from the test rig.

When making measurements with the analyzer it is always a good idea to drive it from a laptop running off its battery. The power supply in a desktop PC that we tried using created a large amount of interference, both radiated and conducted, that upset the measurements. We examined the spectrum from 10 kHz to 1 MHz: at higher frequencies we did not observe any significant power.

In the spectral plots the green curve shows for reference the background noise measured by the test rig with the LED not supplied with power. The spectral plot for lamp 1, shown in Figure 20, is interesting: there is a clear peak at 44.76 kHz (the lamp's internal switching frequency) and its harmonics. Above the fourth harmonic the background noise level starts to rise, but it remains below –80 dBm. Spectral plots obtained from other lamps are similar in appearance and do not provide much in the way of further insight, although lamp 12 distinguishes itself by having a noise floor some 8 dBm higher than its companions.

You may be wondering: what about the spectrum from lamp 2? Figure 21 reveals the awful truth: interference at powers of up to –43 dBm. Even the internal switching frequency is drowned out in the sea of broadband RF noise. It's hardly surprising that a lamp like this makes radio reception nearby practically impossible.

Low-frequency magnetic fields

Figure 22 shows the test set-up to measure magnetic fields at frequencies from 10 kHz to 1 MHz. The magnetic field sensor is an off-the-shelf 68-µH ferrite-core coil mounted 5 cm from the lamp under test. As always lamp 1 behaves in an exemplary fashion, and Figure 23 shows the clean magnetic spectrum measured from lamp 10. The fundamental of the switching frequency is hardly visible, and at higher frequencies the level of interference is pleasingly low. As before, the green curve shows the measured background signal with the lamp switched off as a reference.

Turning to the bad boys: the results from lamp 12 shown in Figure 24 reveal an array of harmonics across the entire measured bandwidth. And, as might be expected, lamp 2 (results in Figure 25) steals the show from a magnetic point of view.

Incidentally, lamps 5 and 6 show almost no stray magnetic field, which is probably because, as mentioned earlier, they do not contain switching power supplies.

High-frequency magnetic fields

Our investigations into magnetic fields did not stop at 1 MHz: we also examined the spectrum from 1 MHz all the way out to 110 MHz. For this experiment we replaced the ferrite-core coil with a more suitable air-core coil of five turns on a 3-cm diameter. With the lamp turned off we observed a spike at 24 MHz: bear that in mind when looking at the spectral plots.

The results from lamp 10 (Figure 26) and lamp 13 (Figure 27) are particularly noteworthy. From Figure 26 we see that lamp 10 produces broadband magnetic interference but at a low enough level not to disturb other equipment. More wor-

rying is lamp 13, which shows a considerable level of interference between 14 MHz and 17 MHz. And, as ever, lamp 2 is pretty bad: even the background spike at 24 MHz does not make it through the noise it produces, as shown in Figure 28.

Electromagnetic interference

It is also important to find out what we can pick up in the way of electromagnetic interference using an antenna. For these experiments we used a 50 cm whip antenna mounted 50 cm from the lamp under test as a sensor, and we extended the frequency range we examined to 220 MHz. Although the experiments were carried out in a basement room that provided good electromagnetic attenuation, there were still background signals at several frequencies, as shown by the green reference line in our spectral plots. To get useful measurements for the better specimens among our test set we had to enable the preamplifier on the spectrum analyzer. We then saw some interference at 10 MHz from the laptop's mains power supply; unfortunately by this point in the series of tests the machine's battery was running low. Two of the lamps produced striking results. Figure 29 shows the result from lamp 11: a slightly increased level of interference above 100 MHz. Again, lamp 2 (Figure 30) puts in the poorest performance. It is practically impossible to receive broadcast stations on a radio placed near to this lamp.

Miscellanea

When changing lamps in the test rig it became apparent that the lamps differed considerably from one another in weight. Since the fitting and envelope presumably weigh much the same in each case, and the electronics and LED (apart from any heatsink) are fairly light, it must be the case that the difference is down to the transformers, coils and chokes used in the device, which in turn correlates with the effort put into the design. We have listed the weight of each lamp in Table 1: observe that lamp 5 is actually lighter than the incandescent equivalent. We used a photodiode to detect whether the rectified mains frequency (100 Hz) or the switching frequency was present in the light output of each device: the results are listed in the column headed 'Flicker' in Table 1. Even the incandescent bulb exhibited a little flickering at 100 Hz. The light output and power consumption data in Table 1 are as given by the manufacturers, and from these we have calculated the efficiency in lm/W. The best performers here are lamp 3 and the two retro-style lamps, numbers 5 and 6. In no case was the LED's current waveform sinusoidal. In order to verify that the power figures correspond to reality, we tested lamp 1 with a power meter

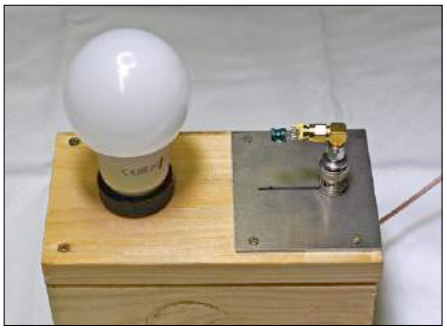

Figure 22. A small coil mounted 5 cm from the lamp is used as a magnetic field sensor.

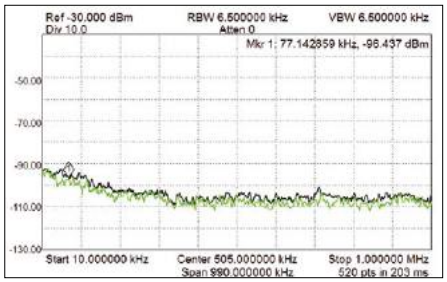

Figure 23. Low-frequency magnetic spectrum from lamp 10: looks good.

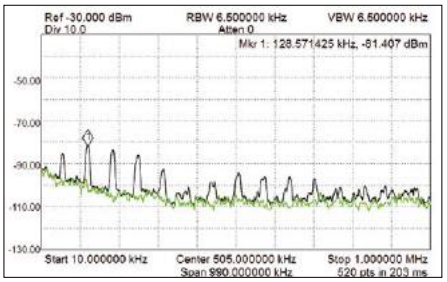

Figure 24. Low-frequency magnetic spectrum from lamp 12: a series of harmonics.

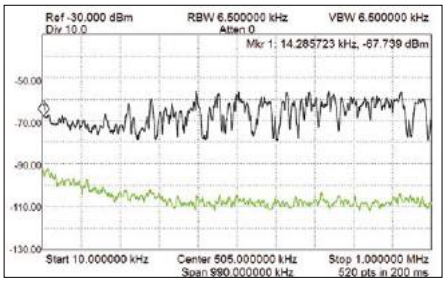

Figure 25. Low-frequency magnetic spectrum from lamp 2: not exactly great.

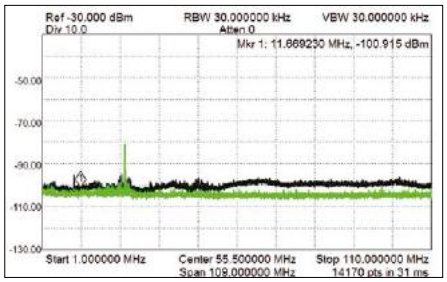

Figure 26. High-frequency magnetic spectrum from lamp 10: some noise at higher frequencies.

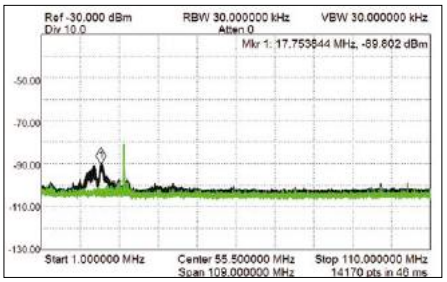

Figure 27. High-frequency magnetic spectrum from lamp 13: peaks at 14 MHz and 17 MHz.

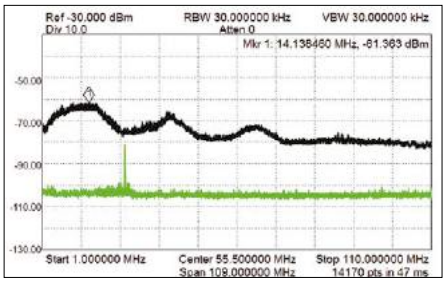

Figure 28. High-frequency magnetic spectrum from lamp 2: it doesn't look good.

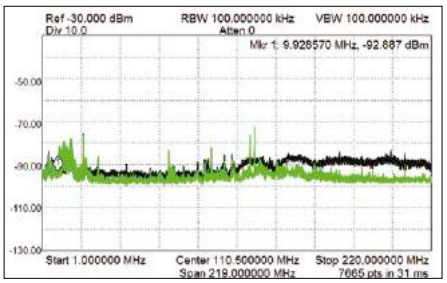

Figure 29. Antenna signal near to lamp 11.

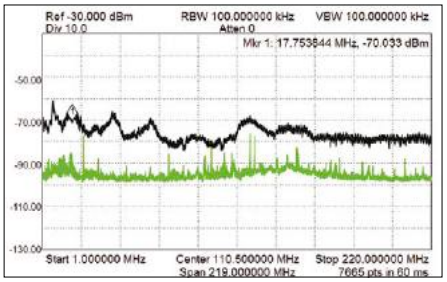

Figure 30. Antenna signal near to lamp 2: an excellent generator of interference.

EMI testing using a radio

In a room with modest VHF reception (the author's basement) we placed a radio about 20 cm from a LED lamp. The antenna was adjusted until the transmitter could be heard without interference, and then the LED was turned on (see image). A short video of this procedure can be seen on the Elektor web pages accompanying this article [4].

As expected, lamp 2 caused a great deal of interference. Lamp 10 caused a small amount of interference and lamps 1, 7 and 11 very little. All the other devices generated no interference at all. In order to hear the effect, it is necessary to listen close to the loudspeaker.

This simple test is surprisingly sensitive, and it is easy to explain to the man in the street how to carry it out and so determine whether an LED lamp is causing radio interference. If a portable radio is not available, the FM radio present in many smartphones will do instead. An ordinary table lamp or similar can be used in place of the mounted socket shown.

Figure 31. EMI testing using an FM radio.

However, FM reception is not the end of the story: with a shortwave receiver we were able to repeat the test at 8 MHz. Here lamp 2 was the only offender; the other lamps were fine. So, although this test does detect the interference from lamp 2, the simple FM radio test is in fact more sensitive.

Modern times demand a modern approach, and so for our third experiment the author's car radio, a DAB+ receiver, was pressed into service. The result of this test was that even lamp 2 did not disturb reception, which illustrates how robust the transmissions are. In FM mode, however, the car radio was not able to pick up a signal in the presence of lamp 2. The other lamps were not tested with this radio.

(a Voltcraft 4500 PRO DE). We measured the power at 10 W rather than the specified 9.5 W, which is acceptably close. Direct calculations from the current and voltage waveforms that we obtained, which should certainly be accurate enough, also indicate that there are no great deviations from the manufacturers' claimed figures.

Conclusion

Happily almost all the LED lamps we purchased for this test exhibit either no interference or so little interference that it can hardly be detected.

Lamp number 2, however, is an excellent generator of interference and should never have graced the supermarket shelf. We cannot be sure, of course, whether this is faulty design or whether our device is an outlier or defective. Things could be worse, however: see the 'Electronic transformers' text box.

If you suspect that a LED lamp is causing radio interference, you can follow the procedure outlined in the 'EMI testing using a radio' text box. If you discover a rotten apple, please write to Elektor at editor@elektor.com with subject line 'LED lamp EMI'. If it is a device that has yet to be tested then we will pass the details on to the author for further investigation, and, if applicable, the results will appear in an update to this article covering a wider range of manufacturers. ⏮

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Web Links

[1] www.elektormagazine.com/news/led-rumpus

[2] www.darc.de/der-club/referate/emv/konformitaetsmessungen/#c201092 *(in German)*

[3] www.elektormagazine.com/150577

[4] www.elektormagazine.com/160610

[5] www.elektormagazine.com/080691

Electronic transformers

Every DIY store should really put up a sign saying 'Beware of electronic transformers'. And no, we are not talking about 'robots in disguise'! No, we mean the devices that are used to power 12-V lighting systems, using halogen spotlights and more recently spotlights and bulbs employing LEDs. Considering their power output they are small, lightweight and cheap. They contain a small switching power supply, but of a special design as you will see if you take a second look at the photo, which comes from an article by Thomas Scherer in the December 2008 issue of Elektor [5].

The circuit lacks a smoothing capacitor on its input and a filter capacitor on its output. The latter omission explains why the output is a rather brutal squarewave at 12 Veff (albeit at a frequency of 30 kHz). Connect this output to some spotlights via a few meters of unshielded cabling behind a suspended ceiling and you have optimal conditions for radiating interference. The lack of input smoothing also results in an enormous 100 Hz component in the output signal: and so we have not just interference, but an RF carrier modulated six ways to Sunday by a 100-Hz tone. The result is a not-so-soothing hum at the output of any nearby radio receiver. Astonishingly there seems to be nothing illegal about this set-up, or at least nothing illegal about selling the components: electricians will continue to blithely install such systems while radio amateurs nearby pull their remaining hair out. There is certainly scope for government intervention to prevent these systems becoming more widespread.

Figure 32. The spartan interior of a 12-V electronic transformer.